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THE ISOTROPIC COSMIC MICROWAVE RADIATION AT 2.63 MM FROM OBSERVATIONS OF INTERSTELLAR CN

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Considerable interest has recently been aroused by the suggestion by Dicke et al.[1] that radiation emitted during a contracted stage of the universe may still exist in the form of quasi-thermal microwaves, and by the reported discovery of this radiation, first by Penzias and Wilson[2], and recently by Roll and Wilkinson[3]. Penzias and Wilson give a brightness temperature of 3.5 ± 1.0 ^{o}K at a wavelength of 7.35 cm[3], while Roll and Wilkinson report 3.0 ± 0.5 ^{o}K at 3.2 cm.

It may be possible to make further observations of this faint effect through the atmospheric window around 8 mm, but still shorter wavelength measurements from the ground are excluded by the atmospheric opacity of oxygen and water vapor. If the radiation has a thermal character, however, the flux peaks near a wavelength of 1 mm, and importance attaches to measurements in this region.

It is the purpose of this note (a) to show that in all likelihood the rotational temperature of the interstellar CN violet band, first estimated by McKellar[4][5] over twenty-five years ago to be 2.3 °K, constitutes a good measurement of the cosmic noise at 2.63 mm if the CN exists in normal non-ionized H I regions, but that in ionized H II regions collisions may substantially contribute to the rotational temperature; and (b) to report a new measurement of the CN temperature that we have made recently with the McMath Solar Telescope of the Kitt Peak National Observatory. This measurement, which was made with the help of W.C. Livingston and C.R. Lynds, gives $T = 3.75 \pm 0.\underline{40}$ 50 °K — for the interstellar lines seen against the star ζ Ophiuchi[6].

The resonance lines of a number of atoms, and of the molecules CH, CH^+, and in a few cases CN, are observed in the interstellar medium. The resonant R(0) line of the CN violet transition $X^2\Sigma^+ \rightarrow B^2\Sigma^+$ at 3874.6 Å was observed by Adams[7] and Dunham[8] against seven stars in their extensive survey of interstellar lines. Against ζ Ophiuchi the sensitivity was sufficiently high to show in addition the R(1) line just to the blue at 3874.0 Å. The lower level of this transition is the J = 1 rotational level of the electronic-vibration ground state which is 3.80 cm^{-1} above the J = 0 level. If the lines are unsaturated the rotational temperature is found directly from the ratio of the R(1) to the R(0) line intensity.

Fig. 1 shows a composite of two spectra of ζ Ophiuchi taken on Feb. 2 and 3, 1966 using the Solar Telescope and its vertical spectrograph in second order. An image intensifier tube was employed which allowed the exposure time in either case to be rather short -- about forty minutes[9].

Measuring the ratio of the equivalent width of the R(0) to the R(1) line to be $r = 2.15 \pm 0.65$ we calculate the rotational temperature to be

$$T = \frac{2hB}{k\ln(2r)} = 3.75 \pm 0.50\ ^{o}K\ , \qquad (1)$$

where $B = 5.70 \times 10^{10}$ cps is the rotation constant for CN[10]. Since only $\ln 2r$ appears in (1) the rotational temperature is rather well determined in spite of the modest signal-to-noise ratio of Fig. 1. The temperature we find is in reasonable agreement with the measurement of Field and Hitchcock[6], and the radio results, as shown in Fig. 2.

No great importance in the past was attached to the observed CN rotational temperature because a number of non-thermal processes exist in the interstellar medium which can excite molecules to higher rotational states. On the other hand CN will be a good thermometer at 2.63 mm for thermal radiation at a level of a few degrees Kelvin if the radiative lifetime of the $J = 1$ state is short compared to the time a molecule will rest in the ground state before non-thermal excitation to any higher rotational, vibrational, or electronic level. We will now show that this condition is fulfilled in typical H I regions for optical fluorescence and collisions with H atoms, but is probably not fulfilled in H II regions if the density is as high as $1/cm^3$.

Radiative Lifetime of the CN Rotational Levels

The lifetime of the rotationallevels of a polar diatomic molecule is given by

$$\tau_J = \frac{3hc^3}{512\pi^4} \frac{1}{\mu^2 B^3} \left(\frac{2J+1}{J^4}\right) , \qquad (2)$$

where μ is the dipole moment in esu, and B is the rotation constant in cps. Since the $^2\Sigma$ electronic ground state of CN is a good example of Hund's case (b), the fine structure of the rotational levels is small and need not be considered.

The dipole moment of the CN ground state has not been measured. An estimate of 0.2 D for the dipole moment of the first excited $^2\Pi$ state, however, has recently been obtained from pressure broadening of microwave transitions observed in a CN flame(11). If the red CN band, the transition $X^2\Sigma^+ \rightarrow A^2\Pi$ consists of breaking the triple bond and transferring the electron to a σ orbital attached to the carbon atom, it can be argued that the smallness of the $^2\Pi$ dipole moment is evidence that the moment of the ground state is large, at least as large as 1 Debye. The only reliable theoretical method for obtaining μ, however, is to do the full molecular orbital calculation, which might be expected to give μ to an accuracy of perhaps 20%(12). The dipole moments of OH and CH have recently been measured to good precision by Phelps and Dalby(13) by observing the optical first order Stark effect; this technique is probably of insufficient resolution for CN where the Stark effect is second order(14).

If we write μ in Debye, (2) becomes

$$\tau_J = 5.8 \times 10^4 \left(\frac{1}{\mu^2}\right) \left(\frac{2J+1}{J^4}\right) \text{ sec} . \qquad (3)$$

Table I gives the lifetimes in seconds of the $J = 1$ level for various values of μ from 0.1 to 2.0 D.

TABLE I

μ(Debye)	0.1	0.2	1.0	2.0
τ_1(sec)	1.74×10^7	4.35×10^6	1.74×10^5	4.35×10^4

Resonance Fluorescence

Both the red and violet bands of CN have been extensively studied in the laboratory, and it is therefore possible to calculate the probability for resonance fluorescence of CN in the interstellar medium if the black-body temperature and dilution factor of starlight are known. The f value for the red band[15] is measured to be 0.0034, and that of the violet band[16] 0.027 ± 0.003.

The time a molecule will rest in the ground state before fluorescence occurs is

$$\tau_{f1} = \frac{mc\lambda^2}{8\pi^2 e^2 \xi f}\left(e^{\frac{hc}{\lambda kT}} - 1\right), \tag{4}$$

where λ is the wavelength of the transition, and ξ and T are the dilution factor and effective temperature of starlight.

Taking $\lambda = 3874$ Å, $\xi = 1 \times 10^{-15}$, and $T = 1 \times 10^4$ °K, we find for the violet band, in which fluorescence is most likely to occur, that $\tau_{f1} = 3.3 \times 10^9$ sec. This is about 200 times longer than the lifetime of the $J = 1$ state in the unfavorable case where $\mu = 0.1$ D, and it is therefore improbable that fluorescence can account for the observed rotational temperature.

Rotational Excitation by H Atoms in H I Regions

The time between collisions with neutral atoms is given approximately by

$$\tau_H \approx 1/nv\sigma \,, \tag{5}$$

where v is the mean velocity, and σ is the cross section for rotational excitation. From microwave pressure broadening studies we expect σ to be about 1×10^{-15} cm^2. Taking $n = 1$ atom/cm^3, typical of non-ionized interstellar regions, and $v = 1 \times 10^5$ cm/sec, (5) gives $\tau_H \approx 1 \times 10^9$ sec, again considerably longer than any of the lifetimes listed in Table I. It is clear that rotational excitation by atoms contributes to the rotational temperature only if the CN exists in regions where the neutral particle density is in the range $10^2 - 10^4$/cm^3, depending on the exact value of μ.

When we turn to ionized H II regions the situation is far less favorable due to the long range of the Coulomb force. The various cross-sections for excitation of CN have not been measured, but may be calculated approximately, or estimated from the results of measurements on similar diatomic molecules.

Excitation by Slow Electrons in H II Regions

Although considerable experimental[17][18] and theoretical study has been devoted to the rotational excitation by electrons of homonuclear molecules (mainly H_2 and N_2), there has been little work on the excitation of polar molecules. Some time ago Massey[20] calculated using the Born approximation that the cross-section for excitation of a symmetric top in the J = 0 ground state is

$$\sigma = \frac{8\pi^3 me^2}{h^2} \frac{\mu^2}{E} \ln(2E/hB) \ , \qquad (6)$$

where E is the electron energy, and B is the rotation constant in cps. This relation is valid as long as $\mu << 1.2 \times 10^{-18} = 1.2$ D, but should at least represent an upper limit for μ large. It is in rough accord with the fractional energy loss observed for polar molecules in electron swarm experiments[18]. Taking E = 1 volt, typical of H II regions, and writing μ in Debye, (6) gives $\sigma = 5 \times 10^{-15} \mu^2$ cm^2. The ratio of the lifetime of the J = 1 state, τ_1, to the time between collisions that excite rotation, τ_{er}, is then given by (5) and (3) as

$$\tau_1/\tau_{er} \doteq 5 \times 10^{-2} n \ ,$$

which is independent of the dipole moment. In regions where n approaches 20 electrons/cm^3 there may thus be an appreciable contribution to the rotational temperature due to electrons, particularly if μ is small.

The mechanism for the excitation of molecular vibration by slow electrons is poorly understood, and it appears that early calculations[21] of cross-sections gave values considerably smaller than those observed[18]. Schulz[22] in electron-beam experiments has observed large and rather broad peaks in the vibrational excitation cross-section for N_2 and CO of the order of 1×10^{-16} cm^2 in the range 1 - 4 ev. If a comparable cross-section applies to CN then vibrational excitation by 1 ev electrons occurs in a time $\tau_{ev} = 2 \times 10^8/n$ sec and this mechanism is comparable to rotational excitation only if μ is small.

Excitation by Slow Protons

The excitation due to protons with energies in the range of 1 ev may be treated classically since the proton wavelength is small with respect to molecular dimensions. Collisions with impact paramters less than the molecular radius, even if effective in exciting higher molecular states, are of relatively small overall importance due to the small geometrical cross-section of the molecule. To calculate the effect produced by the Coulomb field of the proton at large impact parameters it is then possible to use the method of virtual quanta, and it is most revealing to compare the resulting effective intensity of radiation I_p directly to the 3 $^{\circ}$K black-body radiation intensity I_T. We calculate that

$$\frac{I_p}{I_T} = \frac{ne^2c^3}{2\pi h\nu^3 v}\left(e^{\frac{h\nu}{kT}} - 1\right) \ln\left(\frac{0.18v}{\nu b}\right) = 1.5\ n\ , \qquad (7)$$

where $v = 1.38 \times 10^6$ cm/sec, $\nu = 1.14 \times 10^{11}$ cps, and b is the minimum impact parameter, which we take to be 2 Å. This calculation neglects the reaction of the molecule on the proton, but since (7) is rather insensitive to b this is probably inconsequential.

We are led to conclude from (7) that protons represent the most effective mechanism for excitation of CN in H II regions, where their contribution to the observed rotational temperature may be substantial even under normal densities. It is noteworthy in this regard that Sharpless and Osterbrock[23] have found the density of ions in the extensive H II region surrounding ζ Ophiuchi to lie in the range $5 - 24/cm^3$, and that Münch[24] in another instance has been led to propose that CN molecules are being flashed off interstellar grains by an advancing ionization front.

To shed further light on the location of the interstellar CN, and the question as to whether the observed rotational temperature is an accurate measure of the cosmic microwaves or only an upper limit at 2.63 mm, it is clearly necessary to systematically study the several stars which show CN lines, and if possible under sufficient resolution to exclude the possibility of saturation. It is gratifying in this respect that Field and Hitchcock[6] have now measured the rotational temperature for ζ Persei and find $T = 3.0 \pm 0.6$ $^{\circ}K$

No other molecule liable to exist in the interstellar medium appears to be as useful as CN for the purpose of studying the cosmic microwaves. The absence of any lines from excited rotational states in CH allows a rough upper limit of 10 $^{\circ}K$ to be set for the black-body temperature at 0.33 mm (Fig. 2). Any diatomic molecule from the CNO group of atoms will have the required rotation constant, but homonuclear molecules have of course no permanent dipole, and the resonance lines of CO and NO lie too far in the ultraviolet to be observed from the ground. Their interstellar lines may well be eventually detected from orbiting observatories, but their dipole moments have been measured in the laboratory, and are known to be small.

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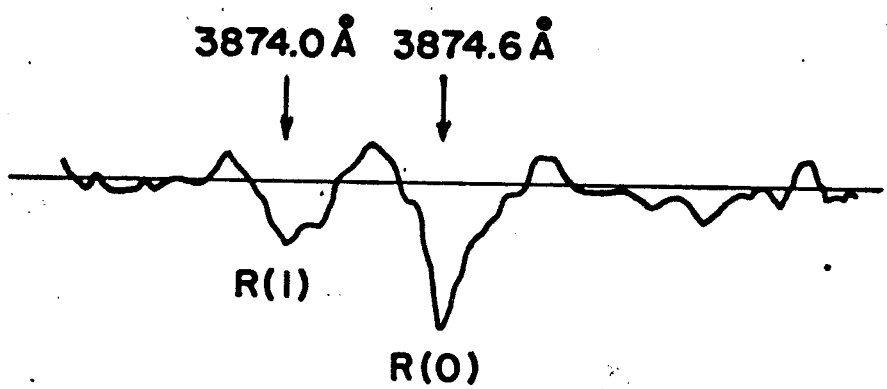
FIGURE CAPTIONS

Fig. 1 The CN violet band in the interstellar medium observed against ζ Ophiuchi with the McMath Solar Telescope.

Fig. 2 Measurements to date of the cosmic microwaves (after Roll and Wilkinson, and Peebles).



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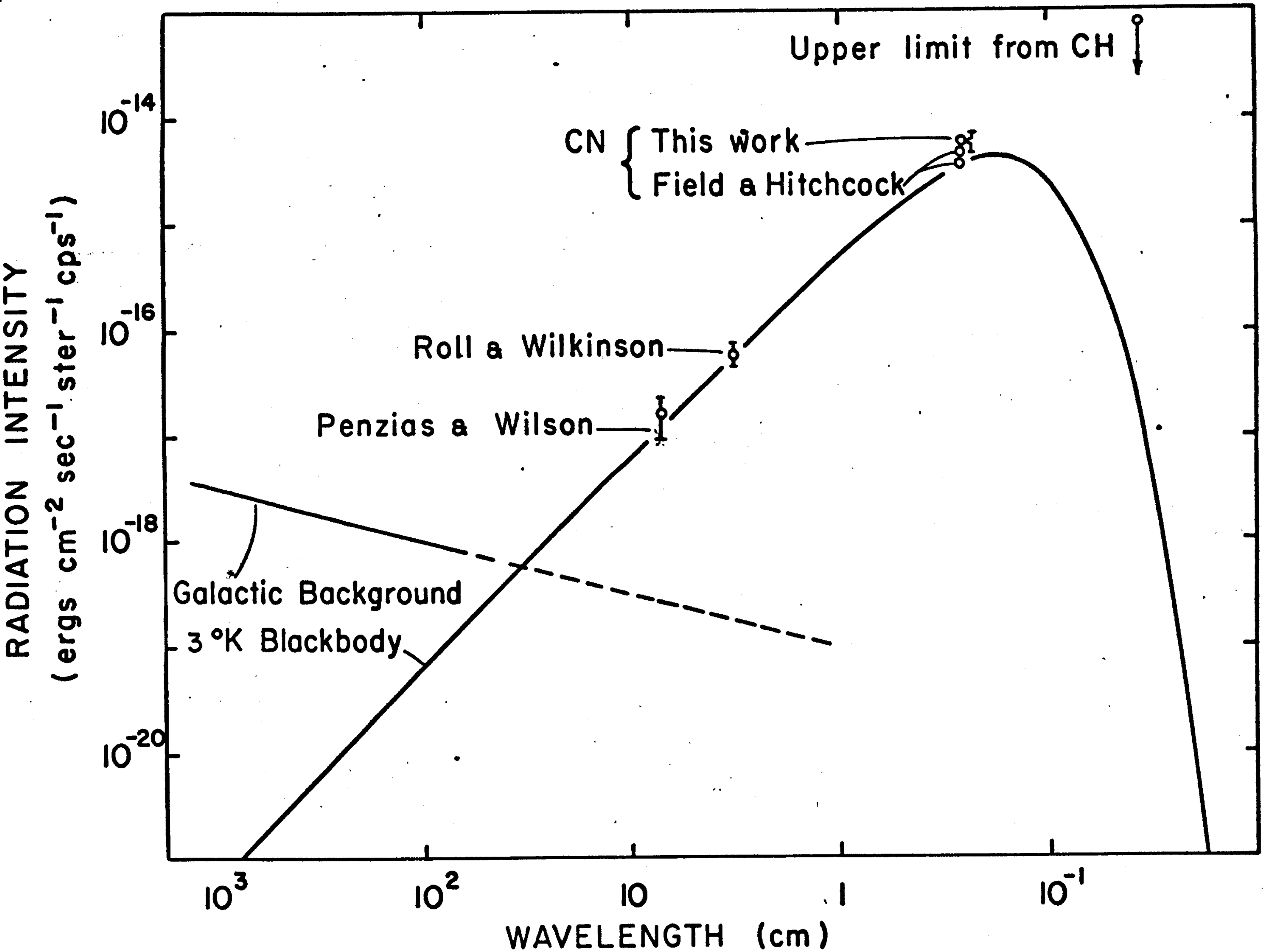

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